Modeling of the laser plasma interaction for the development of efficient EUV sources

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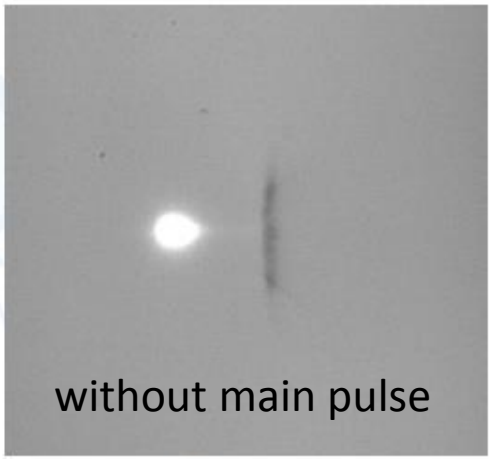
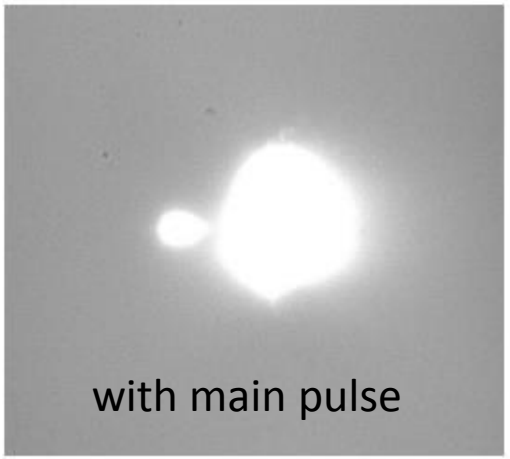
Introduction

- Improvement of efficiency is essential for realization of the EUV lithography.
- Theoretical investigation revealed the spectral characteristics of Sn plasmas, however, much better understanding of laser produced plasmas is needed.
- Modeling of initial laser-matter interaction is required for improving absorption and efficient heating of the plasma.

Modeling hydrodynamics of the plasma

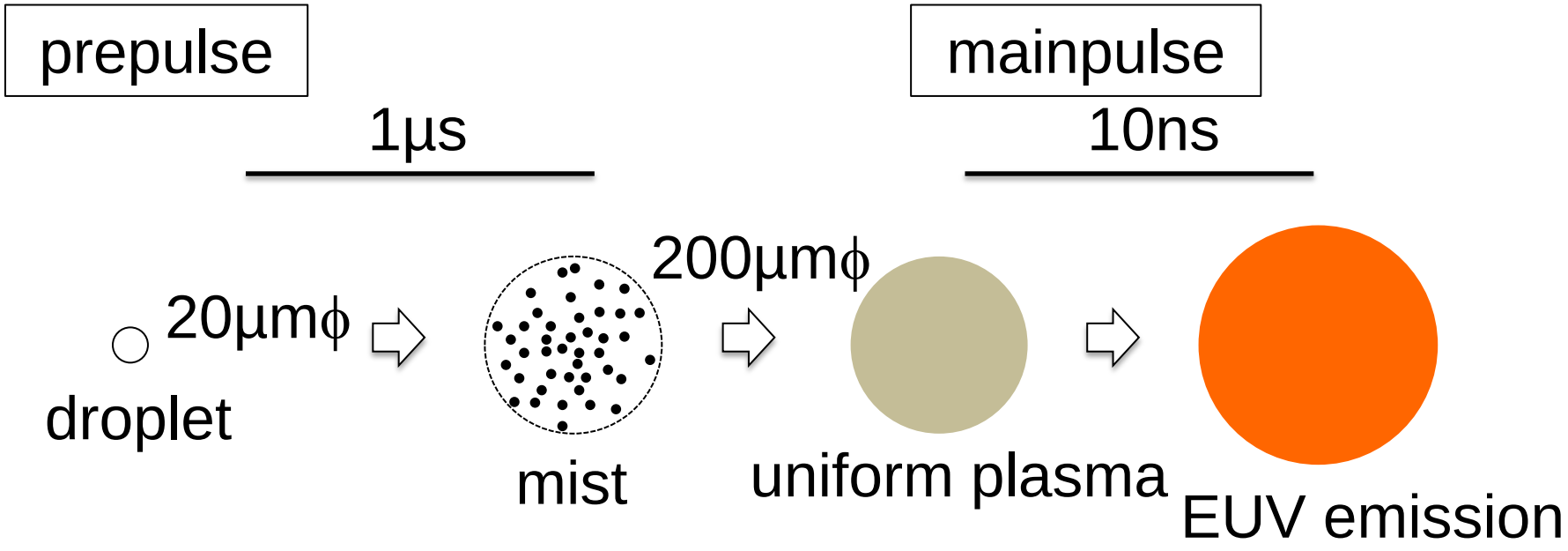
- High efficiency (>3%) is obtained by optimizing double pulse irradiation; pumping Sn particles produced by irradiating small droplet by prepulse.





Endo EUV source workshop 2012 (Gigaphoton data)

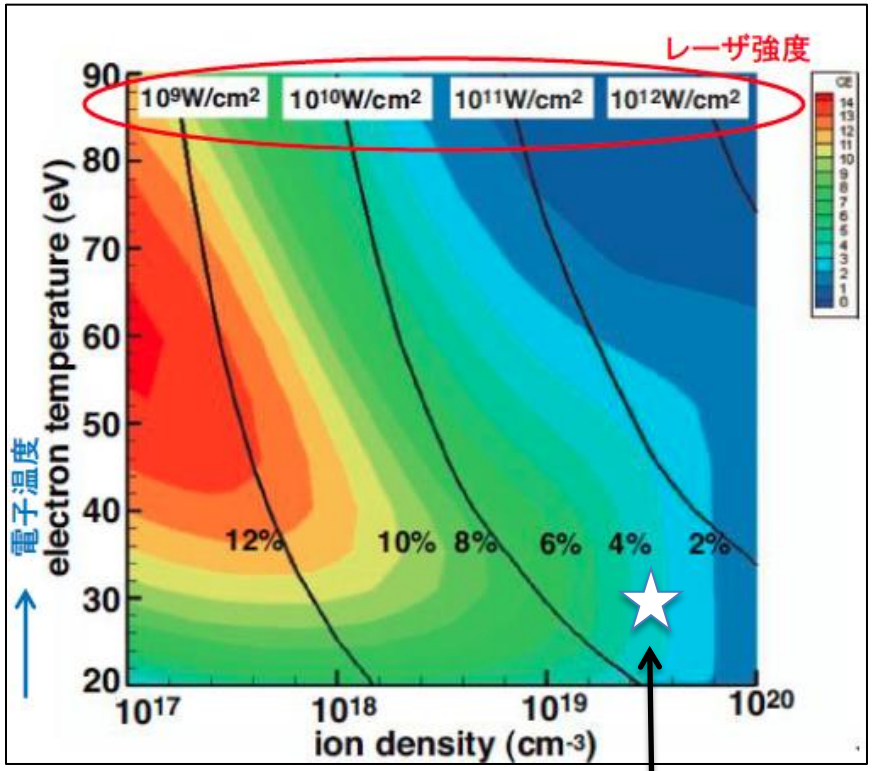
Scenario of excitation of LPP



radius	density
20μm	$3.5 \times 10^{22}/cm^3$
200μm	3.5×10^{19}
2mm	3.5×10^{16}

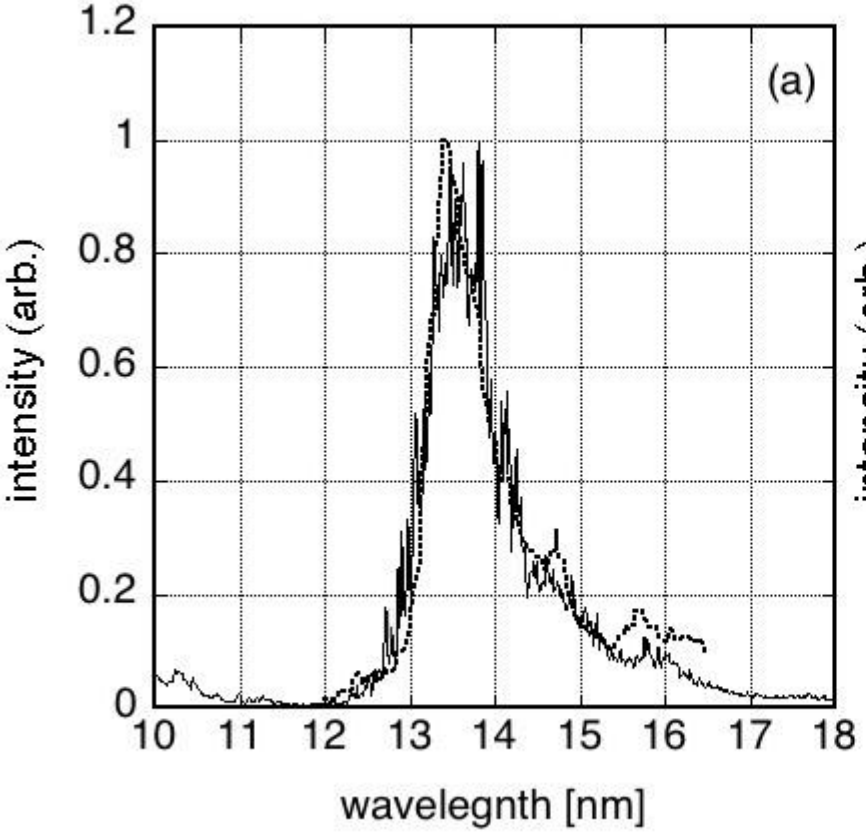
Efficiency can be estimated using power balance model for estimated plasma density

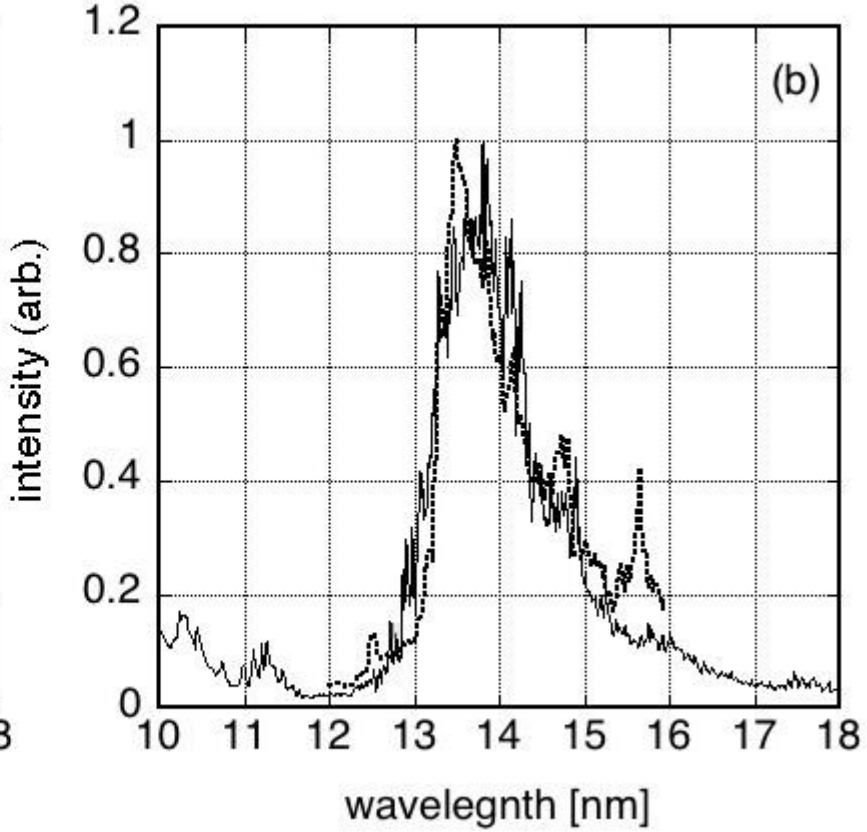
Estimation of conversion efficiency



$n_i=3\times10^{19}/cm^3$
laser intensity $5\times10^{10}W/cm^2$
(150mJ, 10ns, 200μmϕ)

- EUV emission is calculated based on a balance between input laser power and loss of the plasma.
- Experimental efficiency is consistent with those estimated by the power balance model.
- Plasma density can be inferred from measured spectrum.





T_z=18eV, n_i=8.7x10^{17}/cm^3, r=120µm
Tao, Appl. Phys. Lett. 92, 251501 (2008).

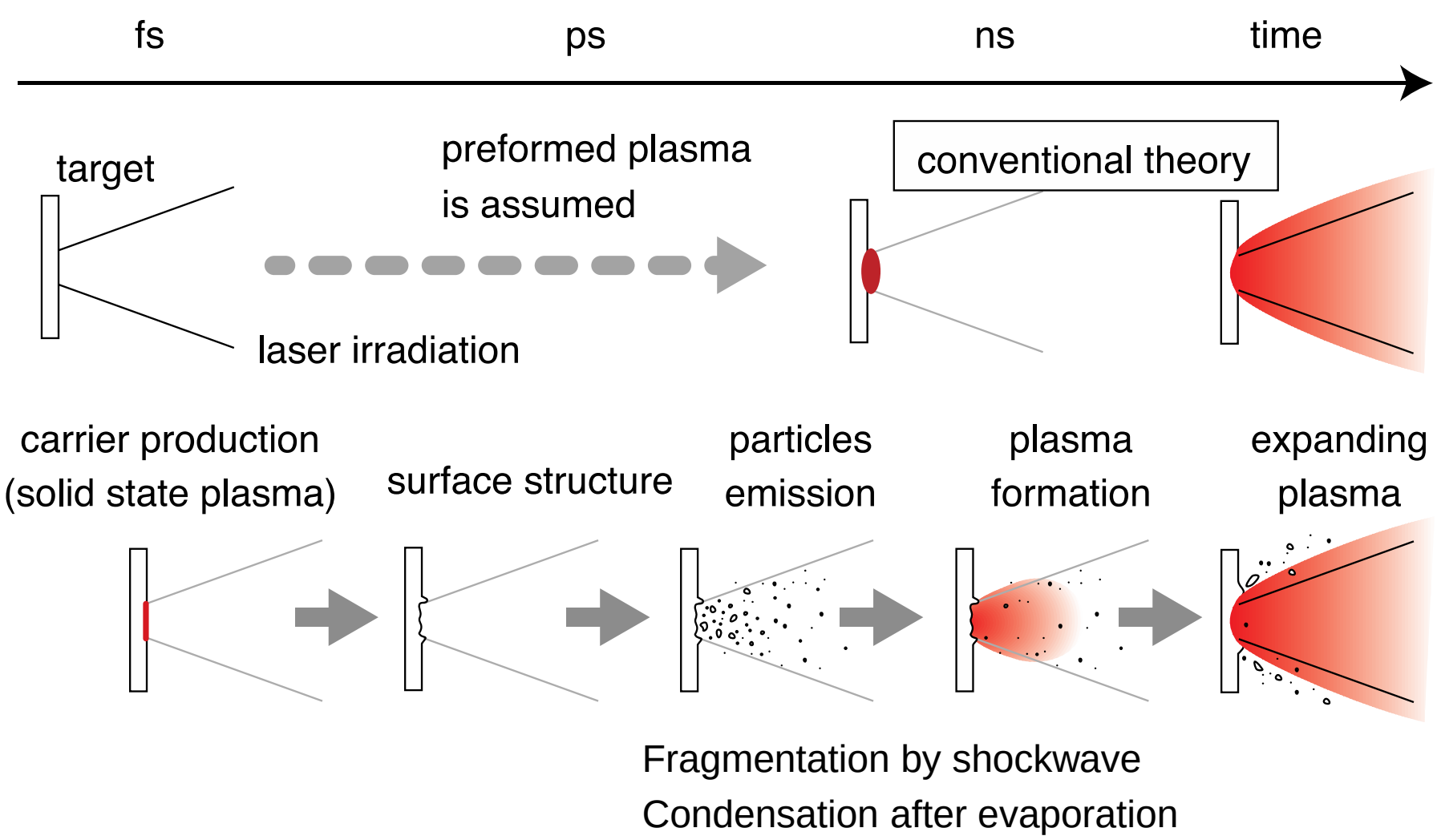
T_z=18eV, n_i=2.6x10^{18}/cm^3, r=60µm
Fomenkov, Proc SPIE 727138 (2009).

A. Sasaki, et al. J. Appl. Phys. **107**, 113303 (2010).

Modeling of coupling of laser and target

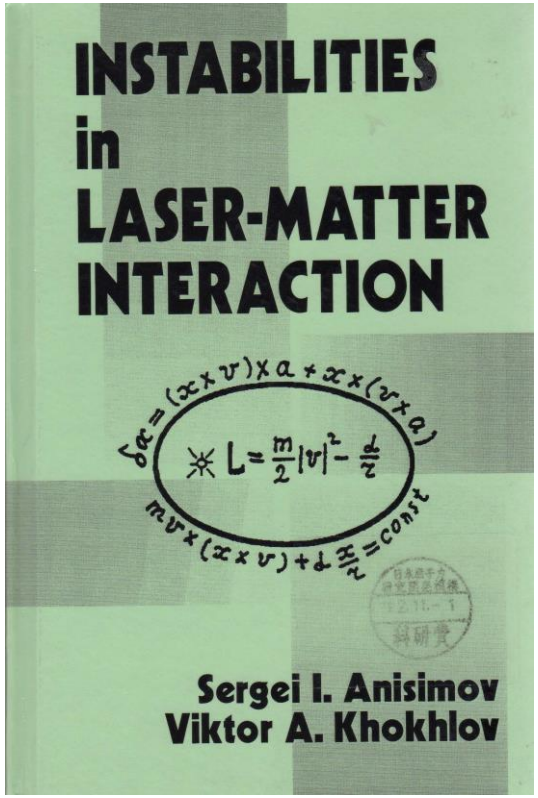
- Formation of particles, and their distribution and interaction with laser should be investigated and optimized.
- Simulation model of interaction of prepulse laser with Sn droplet, particle formation through melting, evaporation, condensation processes should be established.
- Simulation of particles may be useful for debris mitigation.

Modeling of initial laser plasma interaction

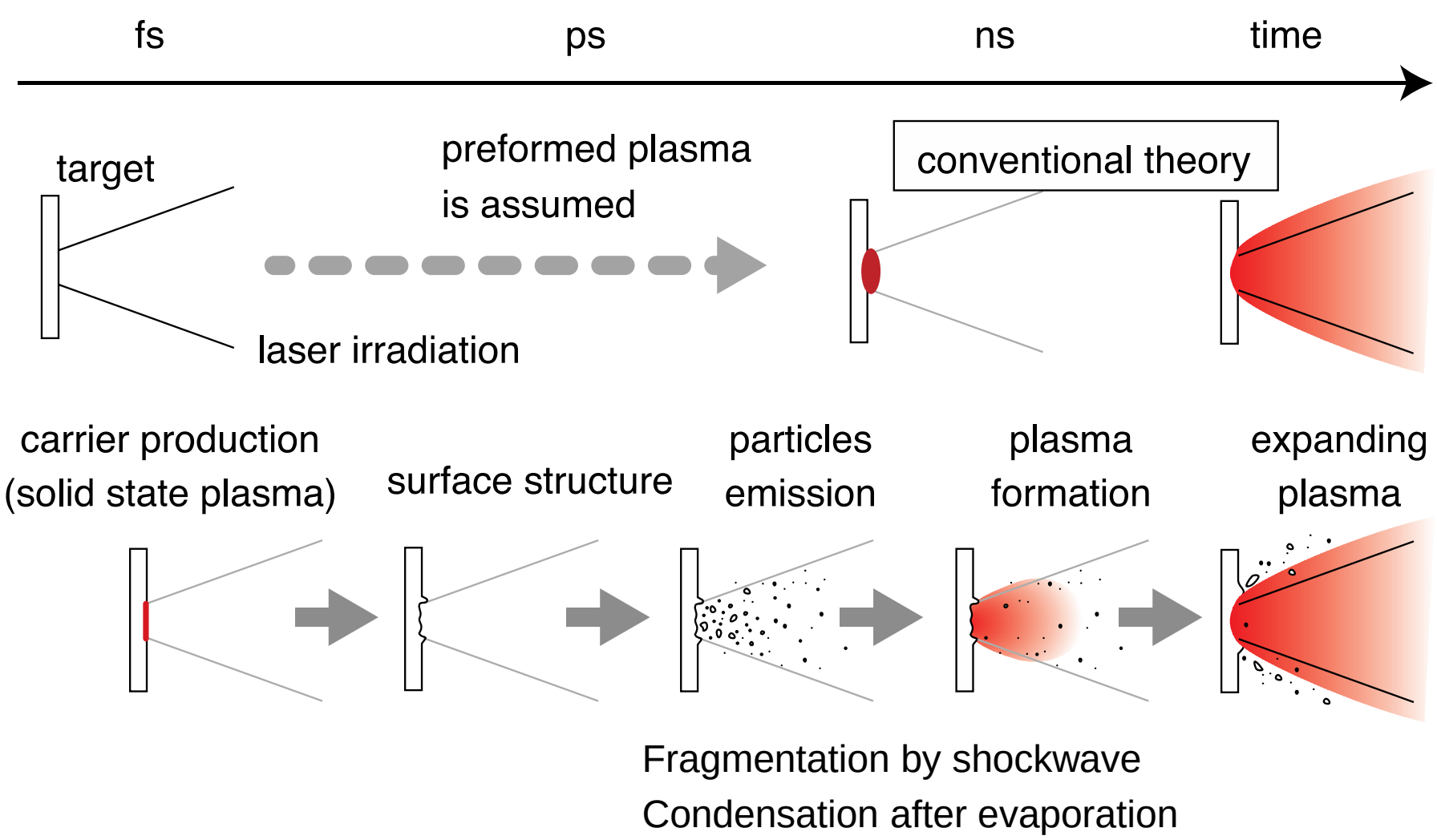


Instabilities in laser plasma interaction

- Instabilities in the initial laser-plasma interaction and subsequent formation of non-uniformities in plasmas has been recognized.
- Instabilities may occur during solid/liquid to gas/plasma phase.

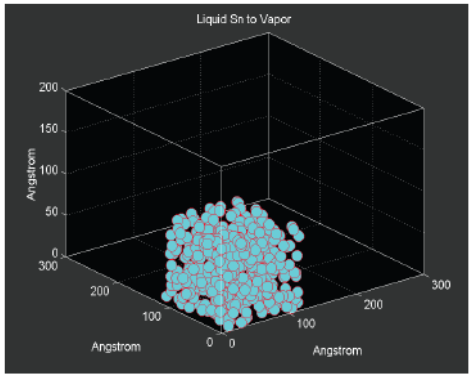


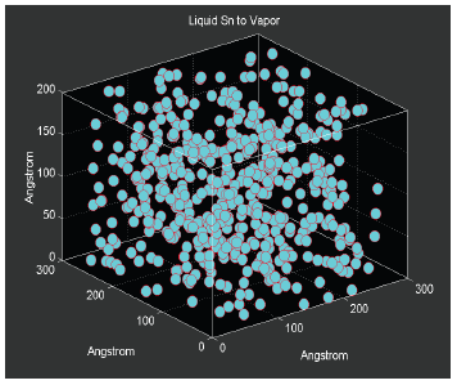
Modeling of initial laser plasma interaction



Simulation of initial plasma formation

- Molecular dynamics simulation qualitatively shows the expansion of droplet, but hydro model is required for evaluation of performance of the source.



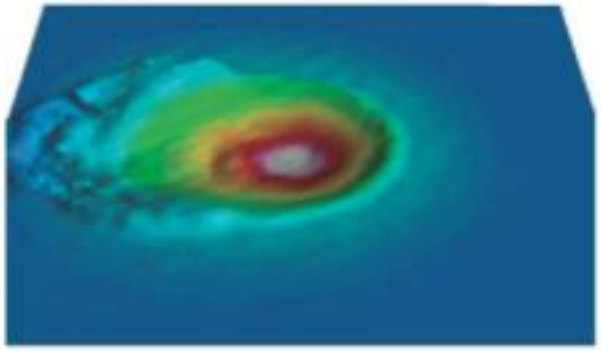


Masnavi, 2009 EUVL workshop

MD

Particle method

Endo, EUVL workshop 2012



Surface tracking

Yamashita, Q .J. Jpn. Weld Soc. 2011

Development of hydrodynamics code

- 2D Lagrangian hydrodynamics model with triangular cells; algorithms of division of the cell is developed to take phase transition of the target material into account.

equation of motion $$\frac{1}{r}\frac{d\mathbf{u}}{dt} = -\nabla P$$

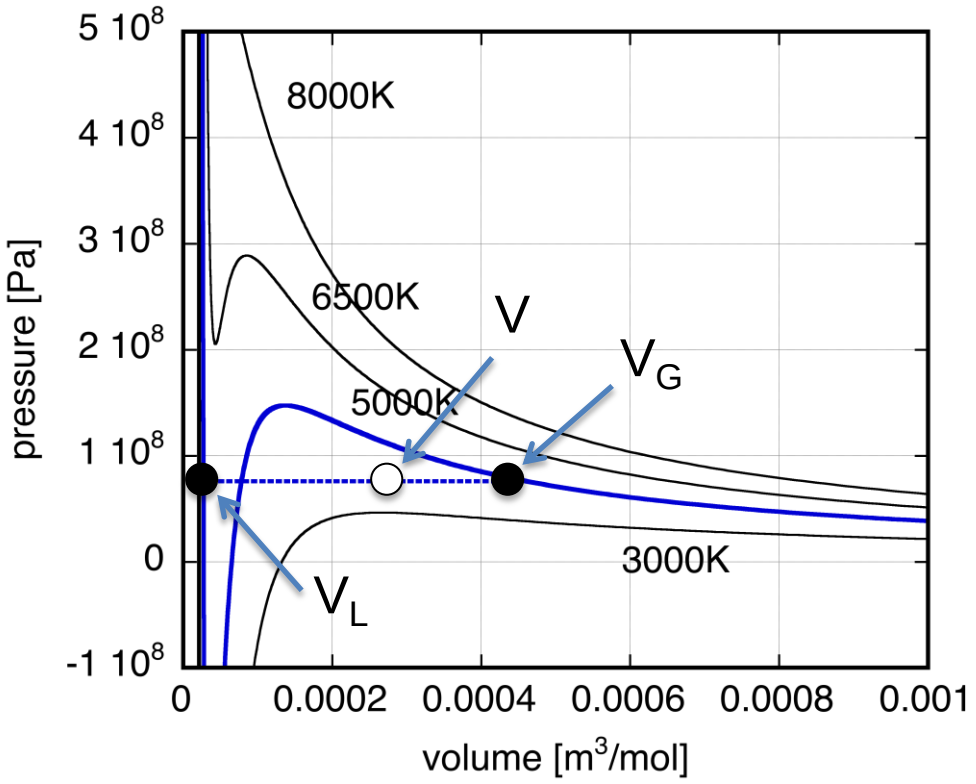
energy equation $$C_V \frac{dT}{dt} + B_T \frac{dr}{dt} + P\frac{dV}{dt} = S$$

Van-der-waals equation of state

assignment of quantities between mesh and cell algorithm for mesh contorl

Van-der-Waals equation of state of Sn

- VW EOS provides universal picture of liquid-gas phase transition with analytical form of thermodynamic quantities.



$$P = \frac{RT}{V_m - b} - \frac{a}{V_m^2}$$

$$a = 3.83$$

$$b = 1.95 \times 10^{-5}$$

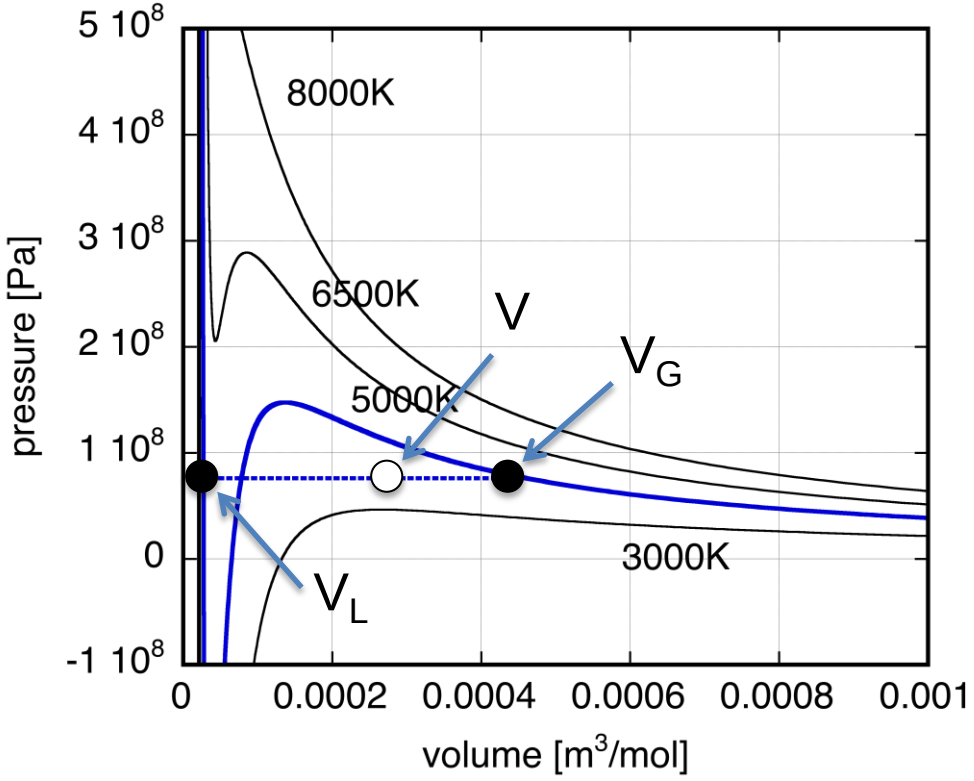
constants are obtained from critical values;

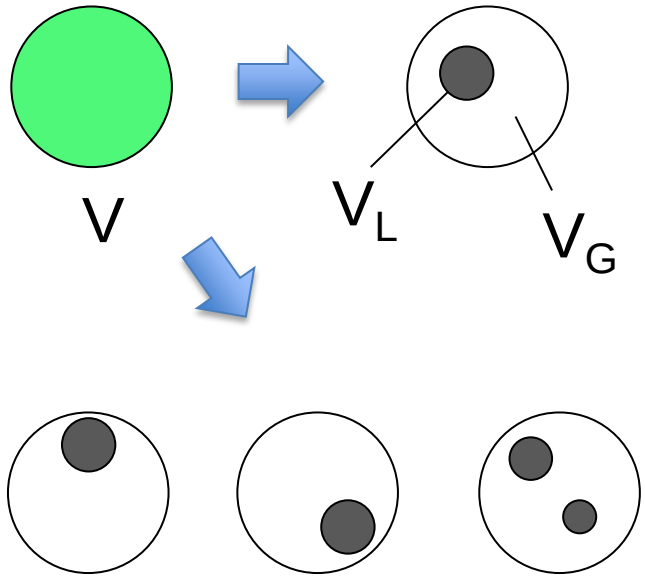
T_c=7300K,

P_c=3.77x10^8 Pa

Structure formation in phase transition

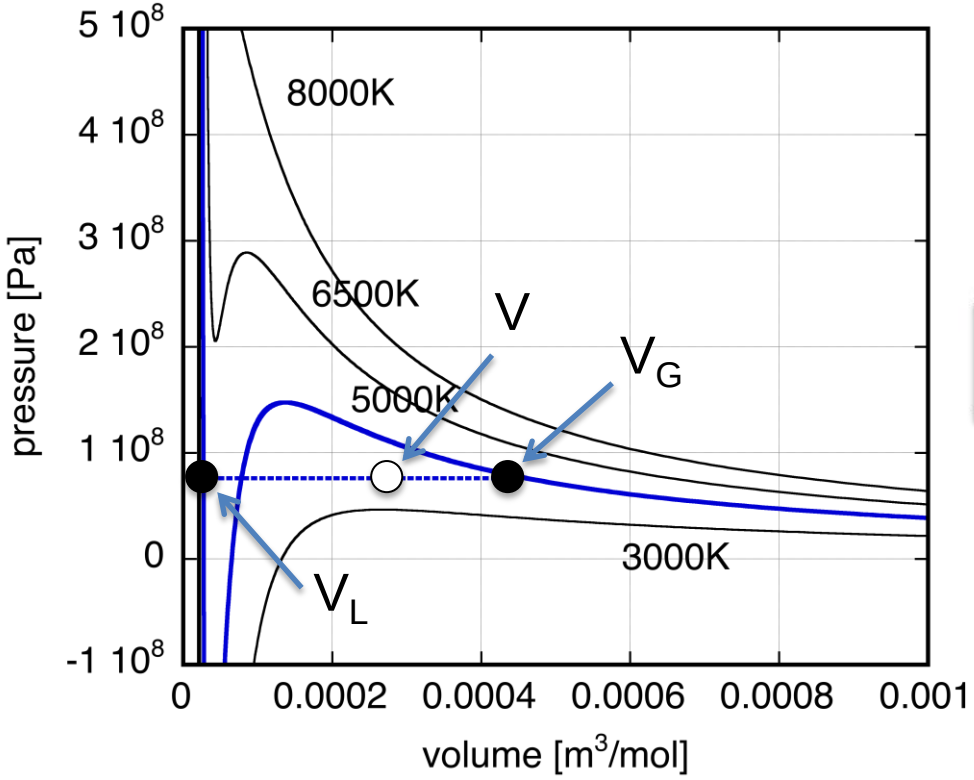
- At the thermodynamic equilibrium, average specific volume of the matter V corresponds to co-existing liquid and gas phase with arbitrary arrangement.



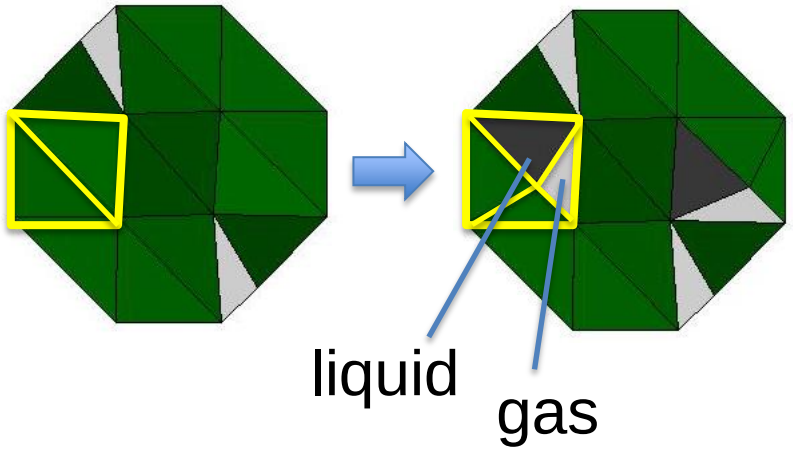


Modeling phase transition

- When a density of a cell becomes those of 2 phase region, the cell is split to liquid (V_L) and gas (V_G) cell.
- Decision of the phase is made based on probability.

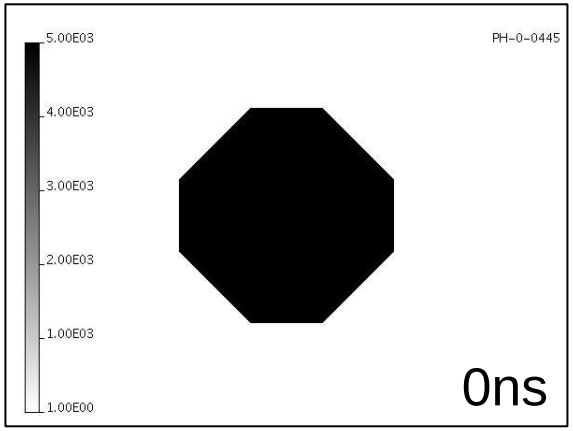


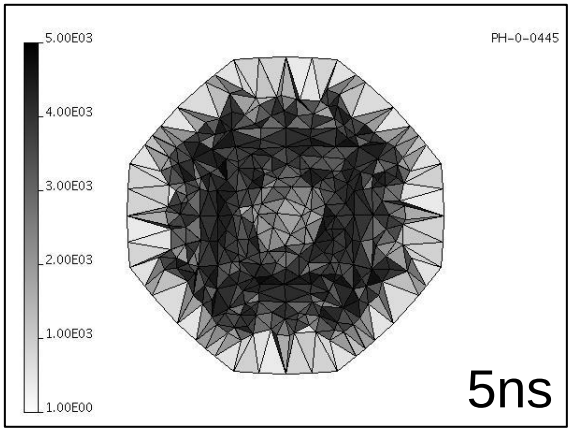
decomposition of mesh

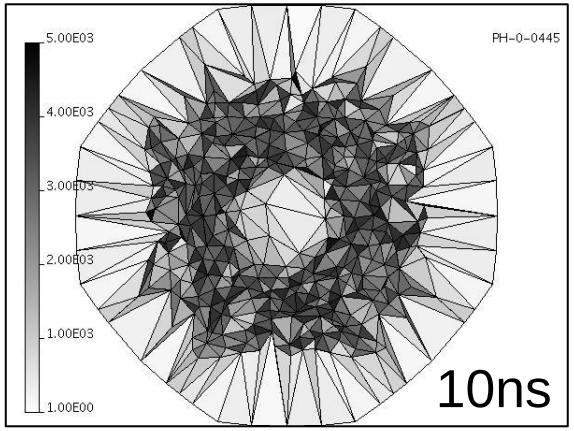


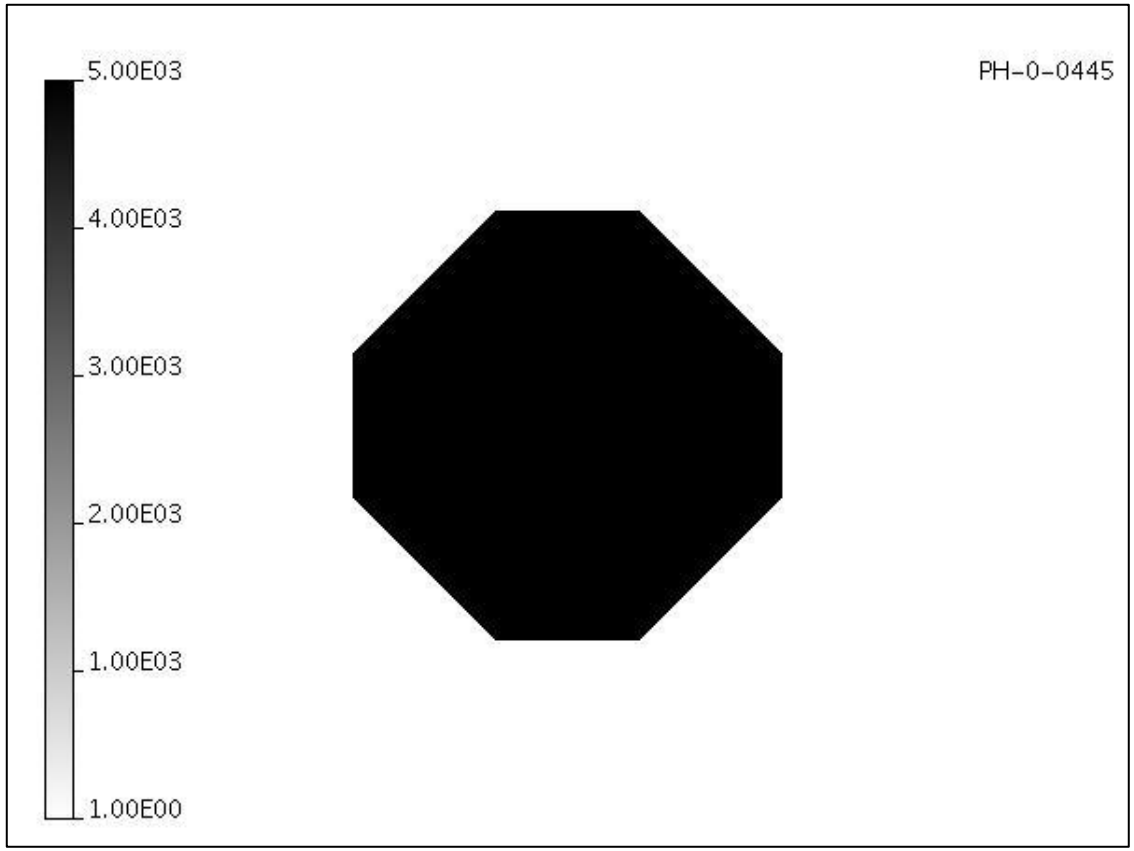
Result of test calculation

- Adiabatic expansion of Sn droplet, r=10μm to 40μm in 20ns, initial temperature = 8000K.





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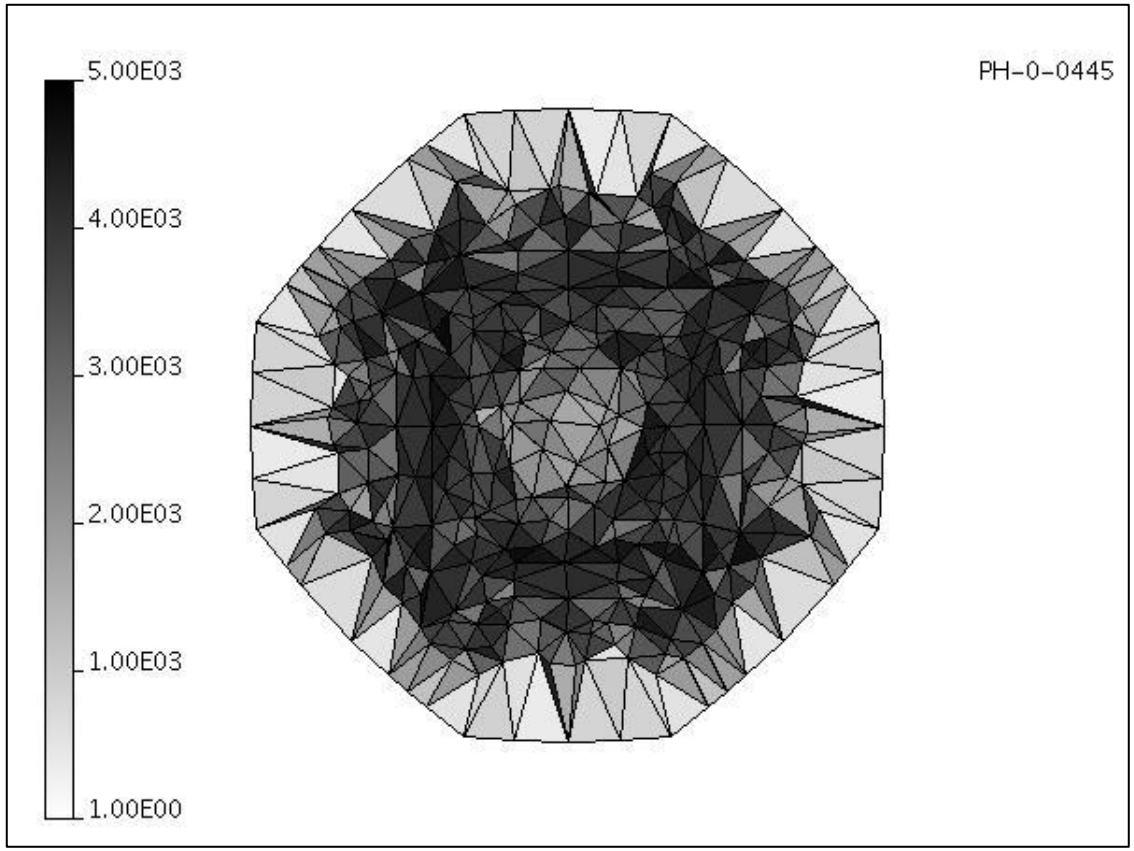
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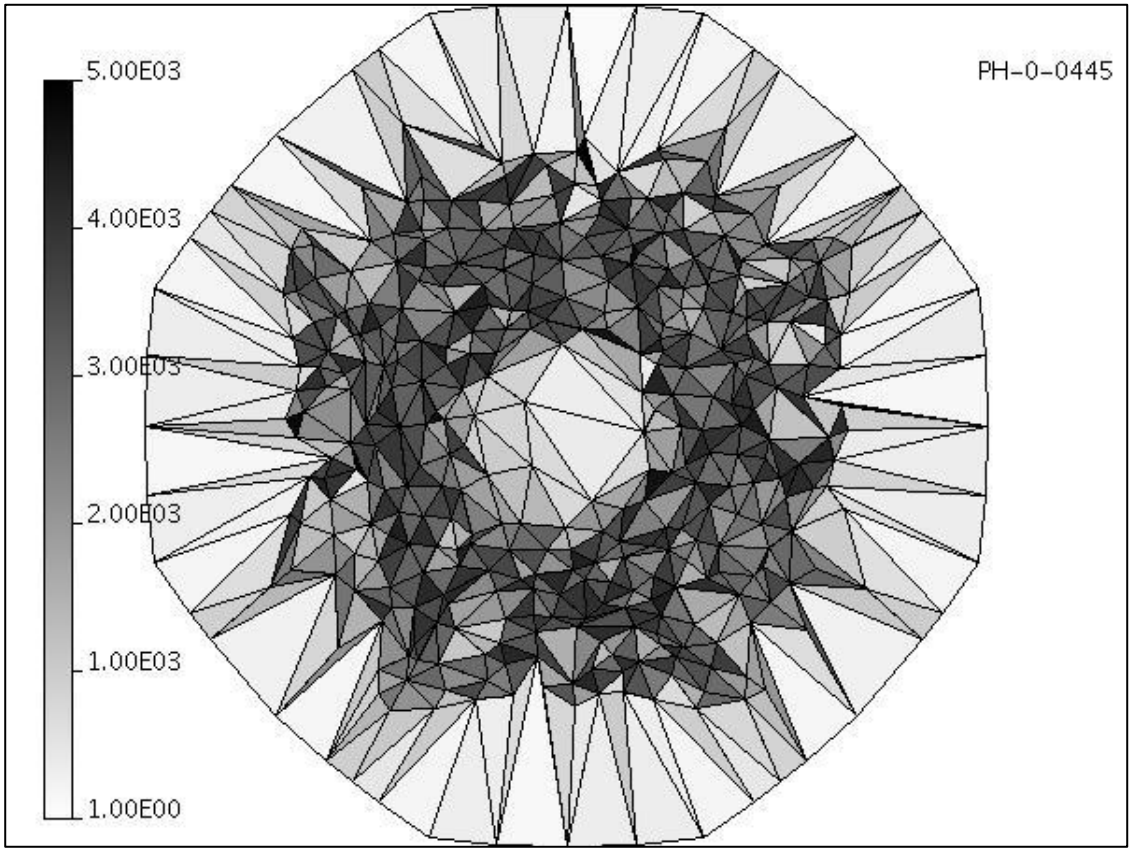
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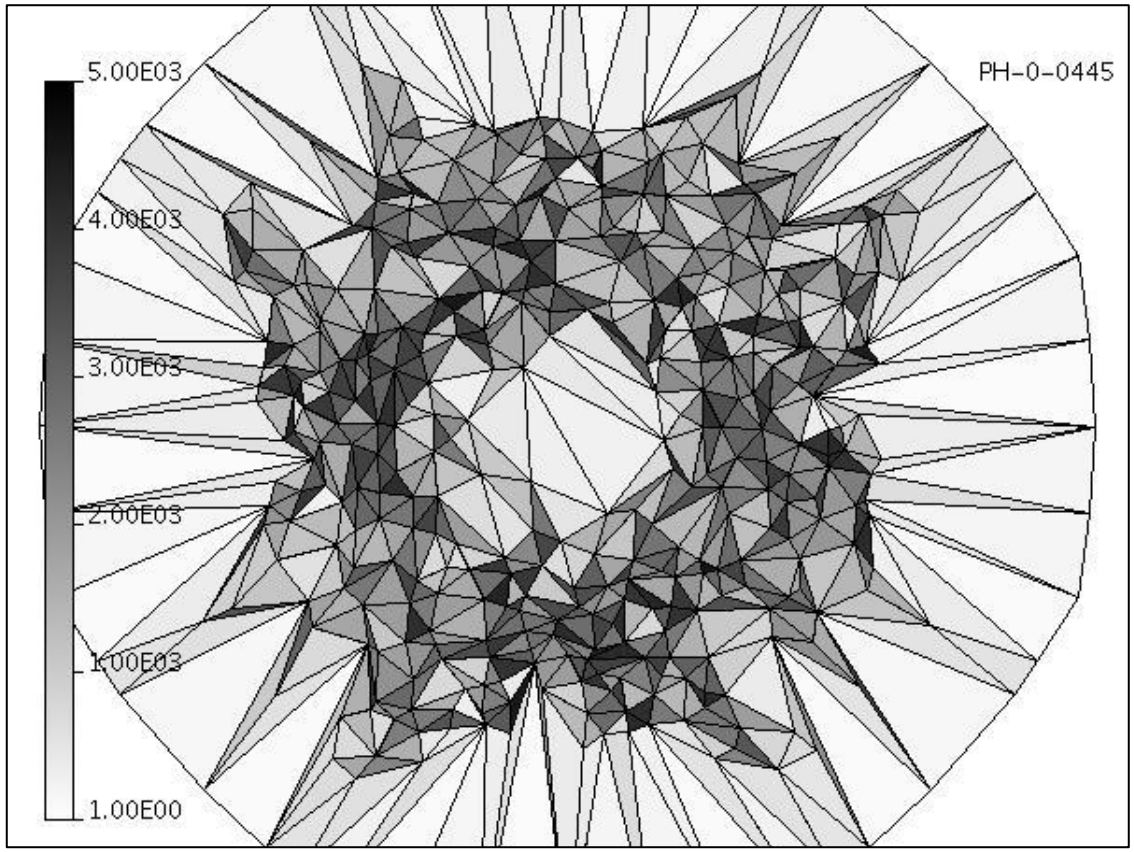
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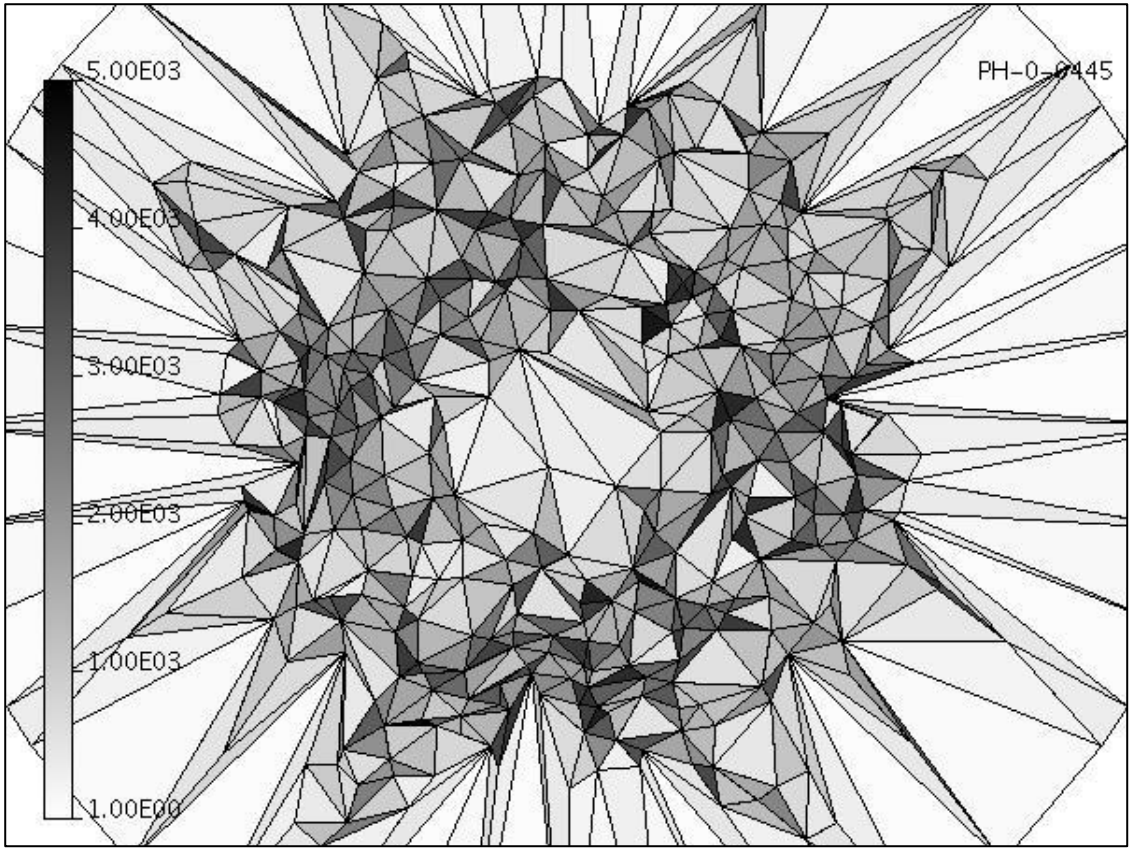
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Present status

- Modeling methods of initial laser plasma interaction have been discussed.
- A method to investigate spontaneous formation of particles through melting, evaporation and condensation processes are being investigated.
- Structure is formed even irradiation is uniform because its property decided by probability.

Future work

- Model of dynamics of phase transition including nucleation will be investigated and included.
- Practical EUV source calculations will be carried out after validation through comparison with experiments.
- Result of present model will provide an initial distribution of the plasma for the radiation hydrodynamics simulation.
- Laser plasma physics will be investigated at the “warm dense” condition and will be included into the model.
- Radiative transfer, which is too computationally intensive, will be investigated.